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**Research Proposal for the
Air Force Office of Scientific Research (AFOSR)
Latin American Initiative**

Final Report 2010

**Aluminum Alloys Reinforced by Nano-Particles
Dispersion**

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Abstract

The synthesis and mechanical-microstructural characterization on nanocomposites was the focus in this project. Nanoparticles of different nature (C and silver nanoparticles) and nanofiber (carbon nanotubes) were used as reinforcement phase. In the beginning pure aluminum matrix was employed to produce nanocomposites, at the end was explored the possibility to scale this results to aluminum alloys (AA2024 and AA7075). Nanoparticles (NPs) dispersion showed an increment in mechanical properties as a function of the NP content. Graphite NPs favor the formation of an apparent aluminum oxi-carbide with amorphous structure. Silver nano particles (AG_C-NP) kept the morphology after all experimental process; this means that AG_C-NP were not dissolved or deformed during processes. In the same case to graphite NP, when AG_C-NP were used as reinforcing phase, an increment in mechanical properties was observed as a function of AG_C-NP content. There are several strengthening mechanisms working in these nanocomposites. Some of them are commented and discussed in published articles.

2.- Objective:

Our research objective is to increase the mechanical resistance of aluminum matrices (focused in aluminum alloys from series 2XXX, 7XXX and pure aluminum) produced by Powder Metallurgy processes without altering the natural ductility and density values of the alloys. The reinforced Al alloys can be used satisfactorily in applications related to aeronautical and aerospace industries, as well as other related industries.

3.- Status of effort

Considerable advances have been reached in the aluminum matrix reinforcement by nanoparticles dispersion, main focus of this project. Nanoparticles (and nanofiber) of different nature has been studied as reinforcement dispersoids. Results of Aluminum-Graphite nanoparticles (GNP), Aluminum-Silver Nanoparticles (Ag-NP) and Aluminum-Carbon nanotubes (CNT) composites are included in the present report. Additionally, in alloys that can be strengthened by precipitation thermal treatment (aging), for example series 7XXX or 2XXX, the first experiments are running, however these results are not reported (published) at this time. Has been found an important effect of solution treatment on mechanical properties in nanocomposites, we expect that after precipitation treatment (Temper T6), obtain better mechanical properties that the initial aluminum alloy (7XXX or 2XXX). At the end of this project were published several scientific articles, includes in the number 6 (Publications).

4.- Accomplishments/New Findings

The main objective of the present research is the reinforcement of aluminum matrix by NP and nanofiber (CNT) dispersion. In this field, an important increment in mechanical properties (tensile, compression and hardness test) by NP and CNT dispersion was observed. The variations in density observed were not important. Presence of NP delays the recrystallization in hot extruded aluminum based nanocomposites compared with pure aluminum after same hot treatment.

In the beginning, pure aluminum as composite matrix was used; however, the experimental procedure was shifted to aluminum alloy, mainly in Al-Cu (2XXX series) and Al-Zn (7XXX series).

Work with aluminum alloys (series 2XXX & 7XXX) still in the beginning step. However, the new results are optimistic and promissory. the mechanical and microstructural characterization after heat treatment are being caring out; the questions are, what is the interaction of nanoparticles with the precipitates, is there an effect of nanoparticles dispersion

in the precipitation sequence?, is there an effect of nanoparticles (or CNT) in the precipitates size?. And one of the most important questions, how is the interaction of dislocations with the nanoparticles or nanofibers (CNT)?. Deep characterization is necessary and our group is working in this direction. At this moment there are publications result of this research project, where the possible strengthening mechanisms are mentioned and discussed.

New opportunity areas are emerged during the course of the present research, for example, what is happening in the interface Aluminum- NTC?. Apparently, there exists an aluminum carbide nucleation at the interphase. It has been found the presence of Al_4C_3 by X-ray diffraction. Identification of this carbide has been reached, the morphology and its composition is under characterization.

We still working in the determination of saturation point, at this moment mechanical properties are increasing as the NP content is increasing as well; however, the maximum amount has not been determined or reached. We report publications about aluminum-based nanocomposites with amounts of CNT or NP in the order of 5 wt. %, however, the saturation point apparently has not been reached.

It is well known that aluminum alloys 2024 and 7075 are susceptible of precipitation strengthening, has been found that CNT and AG_C-NP increase the mechanical resistance in 2024 aluminum alloy, this opens the possibility that with a subsequent heat treatment (T6), will be possible to obtain composite materials (AA2024-CNT or AA2024- AG_C-NP) with novel properties, compared with AA2024 aluminum alloy.

5.- Personnel Supported

The participants implicated in the present project are:

<u>Dr. Roberto Martínez Sánchez</u>	Principal Investigator
Dr. Mario Miki Yoshida	Collaborator
Dr. Jose Martin Herrera Ramirez	Collaborator
M. Sc. Ivanovich Estrada Guel	Collaborator
Eng. Wilber Antúnez Flores	Collaborator

Students:

1. Raúl Pérez Bustamante (M. Sc. Student)	GRADUATED
2. Diana Crisel Mendoza Ruiz (M. Sc. Student)	GRADUATED
3. Caleb Carreño Gallardo (Ph. D. Student)	
4.	

6.- Publications

List of publications (International Journal) in which is acknowledging the economical support from USAF.

1. A. Santos-Beltrán, V. Gallegos-Orozco, I. Estrada-Guel, L. Bejar-Gómez, F. Espinosa-Magaña, M. Miki-Yoshida and **R. Martínez-Sánchez**, *TEM Characterization of Al-C-Cu-Al₂O₃ Composites Produced by Mechanical Milling*, Journal of Alloys and Compounds, Vol. 434-435, (2007), 514-517.
2. M. I. Flores-Zamora, I. Estrada-Guel, J. González-Hernández, M. Miki-Yoshida, **R. Martínez-Sánchez**, *Aluminum-Graphite Composite Produced by Mechanical Milling*

and Hot Extrusion, Journal of Alloys and Compounds, Vol. 434-435, (2007), 518-521.

3. **R. Martínez -Sánchez**, J. Reyes-Gasga, R. Caudillo, D.I. García-Gutierrez, A. Márquez-Lucero, I. Estrada-Guel, D.C. Mendoza-Ruiz, M. José Yacamán, *Mechanical and Microstructural Characterization of Aluminum Reinforced with Carbon-coated Silver Nanoparticles*, Journal of Alloys and Compounds Vol. 438, (2007), 195-201.
4. R. Pérez-Bustamante, I. Estrada-Guel, W. Antúnez-Flores, M. Miki-Yoshida and **R. Martínez-Sánchez**, *Novel Al-matrix nanocomposites reinforced with multi-walled carbon nanotubes*, Journal of Alloys and Compounds, 450 (2008) 323–326.
5. P.G. Ramírez-Cano, I. Estrada-Guel, D.C. Mendoza-Ruiz, J. Reyes-Gasga, M.J. Yacamán, A. Márquez-Lucero and **R. Martínez-Sánchez**. *Mechanical and Structural Characterization of Graphite Coated Silver Nanoparticles-Reinforced Aluminum*. Reviews on Advanced Materials Science, Vol 18 (2008) 276-279.
6. D.C. Mendoza-Ruiz, M.A. Esneider-Alcalá, I. Estrada-Guel, M. Miki-Yoshida, M. López-Gómez and **R. Martínez-Sánchez**. *Dispersion of Graphite Nanoparticles in a 6063 Aluminum Alloy by Mechanical Milling and Hot Extrusion*. Reviews on Advanced Materials Science, Vol 18 (2008) 280-283.
7. C. Carreño-Gallardo, I. Estrada-Guel, M.A. Neri, E. Rocha-Rangel, M. Romero-Romo, C. López-Meléndez, and **R. Martínez-Sánchez**. *Carbon-coated silver nanoparticles dispersed in a 2024 Aluminum alloy produced by mechanical milling*. Journal of Alloys and Compounds, 483 (2009) 355–358.
8. Estrada-Guel, C. Careño-Gallardo, D.C. Mendoza-Ruiz, M. Miki-Yoshida, E. Rocha-Rangel and **R. Martínez-Sánchez**. *Graphite Nanoparticle Dispersion in 7075 Aluminum Alloy by means of Mechanical Alloying*. Journal of Alloys and Compounds, 483 (2009) 173–177.
9. D. C. Mendoza-Ruiz, D. Lardizábal-Gutiérrez, E. Torres-Moye, M. Miki-Yoshida, I. Estrada-Guel and **R. Martínez-Sánchez**, *Characterization of Aluminum-Zinc Alloy Reinforced with Carbon-Coated Silver Nanoparticles*, Journal of Alloys and Compounds, **Submitted**.
10. Estrada-Guel, C. Careño-Gallardo, E. Rocha-Rangel, M. Miki-Yoshida, P. Amezága-Madrid and **R. Martínez-Sánchez**, *Effect of Metallic Addition on Mechanical Properties in an Aluminum-Graphite Composite Synthesized by means of Mechanical Milling*, Journal of Alloys and Compounds, **Submitted**.
11. R. Pérez-Bustamante, C. D. Gómez-Esparza, I. Estrada-Guel, P. Amézaga-Madrid, M. Miki-Yoshida, **R. Martínez-Sánchez**, *Mechanical characterization of Al-MWCNT composites*, Journal of Alloys and Compounds, **Submitted**.
12. C. Carreño-Gallardo, I. Estrada-Guel, Neri M. A., E. Rocha-Rangel, M. Romero-Romo, C. López-Meléndez, M. Miki-Yoshida and R. Martínez-Sánchez, *Effect of solution heat treatment on 2024 aluminum alloy reinforced with carboncoated silver nanoparticles (AgcNP)*, Journal of Alloys and Compounds, **Submitted**.

13. R. Pérez-Bustamante, C. D. Gómez-Esparza, I. Estrada-Guel, P. Amézaga-Madrid, M. Miki-Yoshida, R. Martínez-Sánchez, *Microstructural characterization of Al-MWCNT composites produced by mechanical milling and hot extrusion*, Journal of Alloys and Compounds, **Submitted**.
14. R. Flores-Campos, D. C. Mendoza-Ruiz, M. Martínez-Martínez, I. Estrada Guel, M. Miki-Yoshida, R. Martínez-Sánchez, *Microstructural and Mechanical Characterization in Aluminum 7075 Alloy Reinforced by Silver Nanoparticles Dispersion*, Journal of Alloys and Compounds, **Submitted**.

7. Interactions/Transitions:

a. Participation/presentations at meetings, conferences, seminars, etc.

1. D. C. Mendoza-Ruiz, I. Estrada-Guel, R. Pérez-Bustamante, C. D. Gómez-Esparza, A. Hernández-Gutiérrez, E. Torres-Moye, J. I. Baraja-Villareal, **R. Martínez-Sánchez**. *Compósitos Aluminio-Nanopartículas de Plata Recubiertas con Grafito*. Primer Encuentro Internacional ICM 2007, Instituto Tecnológico y de Estudios Superiores de Monterrey ITESM Campus Chihuahua, 11 y 12 de octubre de 2007.
2. R. Pérez Bustamante, I. Estrada Guel, W. Antúnez Flores, M. Miki Yoshida, E. Torres Moye, J. I. Barajas Villaruel, A. Hernández Gutiérrez, D. C. Mendoza Ruiz, **R. Martínez-Sánchez**. *Propiedades mecánicas de compósitos aluminio-nanotubos de carbono*. Primer Encuentro Internacional ICM 2007, Instituto Tecnológico y de Estudios Superiores de Monterrey ITESM Campus Chihuahua, 11 y 12 de octubre de 2007.
3. D. C. Mendoza-Ruiz, I. Estrada-Guel², P.G. Ramírez-Cano, A. Hernández-Gutierrez, E. Torres-Moye, J.I. Barajas-Villareal, **R. Martínez-Sánchez**. *Caracterización Estructural y Mecánica de Aluminio Reforzado con Nanopartículas de Plata Recubiertas con Grafito*. Instituto Tecnológico de Saltillo. Congreso Internacional de metalurgia y materiales. Saltillo, Coahuila 17, 18 y 19 de octubre del 2007.
4. R. Flores-Campos, D. C. Mendoza-Ruiz, M. Martínez-Martínez, Estrada Guel, M. Miki-Yoshida, **R. Martínez-Sánchez**. *Microstructural and mechanical characterization in aluminum 7075 alloy reinforced by silver nanoparticles dispersion*. Instituto Tecnológico de Saltillo. Congreso Internacional de metalurgia y materiales. Saltillo, Coahuila 17, 18 y 19 de octubre del 2007.
5. Estrada-Guel, D. C. Mendoza-Ruiz, M. Miki-Yoshida, E. Rocha-Rangel, **R. Martínez-Sánchez**. *Nanoparticle Dispersion in 7075 aluminum Alloy*. International Symposium on Metaestable and Nano-Materials, Corfu, Greece, 26-30 August, 2007.
6. D. C. Mendoza-Ruiz, P. Ramírez-Cano, I. Estrada-Guel, R. Ochoa-Gamboa, H. Flores-Zúñiga, M. Miki-Yoshida, F. Paraguay-Delgado, **R. Martínez-Sánchez**. *Interaction of Dislocations with Nanoparticles in Al-based Nanocomposites*. International Symposium on Metaestable and Nano-Materials, Corfu, Greece, 26-30 August, 2007.

7. C. Carreño-Gallardo, I. Estrada-Guel, Neri M. A., E. Rocha-Rangel, M. Romero-Romo, R. **Martínez-Sánchez**. *Carbon-Coated silver nanoparticles dispersed in a 2024 aluminum alloy produced by mechanical milling*. International Symposium on Metastable and Nano-Materials, Corfu, Greece, 26-30 August, 2007.
8. D.C. Mendoza Ruiz, D. Lardizábal Gutiérrez, E. Torres Moye, M. Miki Yoshida, I. Estrada Guel, R. Martínez Sánchez. Characterization of 7075 Aluminum Alloy Reinforced with Carbon-coated Silver Nanoparticles. XV International Symposium on Metastable, Amorphous and Nanostructured Materials, Buenos Aires, Argentina, 6-10 July, 2008.
9. Santos Beltrán, V. Gallegos Orozco, F. Alvarado Hernández, S. Haro Rodríguez, A. Lopez Ibarra and R. Martínez Sánchez. Synthesis and Characterization Of Al-Al₄C₃ Nanocomposites Produced By Mechanical Milling. XV International Symposium on Metastable, Amorphous and Nanostructured Materials, Buenos Aires, Argentina, 6-10 July, 2008.
10. Carreño Gallardo, I. Estrada Guel, Neri M. A. , E. Rocha Rangel, M. Romero Romo, W. Antunez Flores, C. López Meléndez, M. Miki Yoshida and R. Martínez Sánchez. Mechanical characterization of aluminum alloy 2024 reinforced with carbon coated silver nanoparticles produced by mechanical milling. XV International Symposium on Metastable, Amorphous and Nanostructured Materials, Buenos Aires, Argentina, 6-10 July, 2008.
11. R. Flores Campos, D.C. Mendoza Ruiz, M. Martínez Martínez, I. Estrada Guel, M. Miki Yoshida, R. Martínez Sánchez. Microstructural and Mechanical Characterization in 7075 Aluminum Alloy Reinforced by Silver Nanoparticles Dispersion. XV International Symposium on Metastable, Amorphous and Nanostructured Materials, Buenos Aires, Argentina, 6-10 July, 2008.
12. R. Pérez-Bustamante, C.D Gómez-Esparza, I. Estrada-Guel, P. Amézaga-Madrid, M. Miki-Yoshida, and R. Martínez-Sánchez. Microstructural characterization of Al-MWCNT composites produced by mechanical milling and hot extrusion. XV International Symposium on Metastable, Amorphous and Nanostructured Materials, Buenos Aires, Argentina, 6-10 July, 2008.
13. Estrada-Guel, C. Careño-Gallardo, E. Rocha-Rangel, M. Miki-Yoshida, P. Amézaga-Madrid and R. Martínez Sánchez. Effect of Metallic Addition on mechanical properties in an Aluminum-Graphite Composite synthesized by Mechanical Milling. XV International Symposium on Metastable, Amorphous and Nanostructured Materials, Buenos Aires, Argentina, 6-10 July, 2008.
14. R. Pérez-Bustamante, C.D Gómez-Esparza, I. Estrada-Guel, P. Amézaga-Madrid, M. Miki-Yoshida, and R. Martínez-Sánchez. Mechanical characterization of Al-MWCNT composites. XV International Symposium on Metastable, Amorphous and Nanostructured Materials, Buenos Aires, Argentina, 6-10 July, 2008.
15. R. Pérez-Bustamante, F. Pérez-Bustamante, J. M. Herrera-Ramírez, I. Estrada-Guel, P. Amézaga-Madrid, M. Miki-Yoshida, R. Martínez-Sánchez, *Production of Al2024-*

CNTs composites by milling process and their microstructural characterization, XVIII INTERNATIONAL MATERIALS RESEARCH CONGRESS 2009, 16 - 21 August, Cancún, Mexico.

16. R. Pérez-Bustamante, F. Pérez-Bustamante, J. M. Herrera-Ramírez, I. Estrada-Guel, P. Amézaga-Madrid, M. Miki-Yoshida, R. Martínez-Sánchez, *Dispersion of CNTs in aluminum 2024 alloy by milling process*, IV Workshop on metastable and nanostructured materials, August 23-26, 2009, IPN, ESIQUE, México, City.
17. Estrada-Guel, J.L. Cardoso, C. Careño-Gallardo, J.M. Herrera-Ramírez, M. Miki-Yoshida and R. Martínez-Sánchez, *Synthesis and mechanical characterization of aluminum-based composites prepared by mechanical milling and powder metallurgy*, IV Workshop on metastable and nanostructured materials, August 23-26, 2009, IPN, ESIQUE, México, City.
18. Estrada-Guel, J. L. Cardoso, C. Careño-Gallardo, M. Miki-Yoshida and R. Martínez-Sánchez, *Synthesis and mechanical characterization of aluminum-based composites prepared by powder metallurgy*, XVIII INTERNATIONAL MATERIALS RESEARCH CONGRESS 2009, 16 - 21 August, Cancún, Mexico.

8. New discoveries, inventions, or patent disclosures.

None

9. Honors/Awards:

The last September I was promoted to Head of the *Integrity and Design of Composite Materials Department*.

Research Interest Category & Corresponding Program Manager:

Metallic Materials

Dr. Joanne Fuller AFOSR/NA